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# A PILOTED SIMULATION STUDY OF THE EFFECTS OF CONTROLLER FORCE GRADIENT IN VTOL HOVERING FLIGHT

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## SUMMARY

A study of the effect of control force gradient on the VTOL visual hovering task was conducted on the NASA-Ames Research Center Six-Degree-of-Freedom Motion Simulator. Lateral control force-gradient characteristics were evaluated in combination with three different types of stabilization systems: An unstabilized (acceleration) system, a rate-stabilized system, and two attitude-stabilized systems. The effects of gust disturbances were included in the control force evaluation for the attitude systems.

A force gradient of 1.0 lb/in was within the optimum range for all control systems and conditions evaluated in this study.

## INTRODUCTION

The Ames Research Center is engaged in research programs to define control system requirements for VTOL aircraft. Past efforts have been devoted primarily to the definition of control power and sensitivity required for the hover tasks for various control systems (reference 1). It is generally recognized that control force characteristics are also important in specifying the acceptability of VTOL control systems, and this is taken into consideration to some extent in the various specifications documents (i.e. references 2 and 3). What has been lacking for the control systems designer, however, is data to indicate optimum control force characteristics.

Accordingly, a study has been made to determine the effects of variations of lateral control force gradient on the VTOL visual hovering task. The study was accomplished through use of the Ames Six-Degree-of-Freedom Simulator, figure 1, and included variations in lateral control force gradient for each of three types of control system: acceleration, rate, and attitude stabilized systems. Force gradients were also evaluated for attitude systems in the presence of gust type disturbances.

| | |
|---|---|
| C. P. | control power |
| F | force, lb |
| $I_{xx}$ | roll moment of inertia, slug-ft$^2$ |
| L | rolling moment, ft-lb |
| $L_\delta$ | roll control gain, ft-lb/in |
| $L_\delta / I_{xx}$ | control sensitivity |
| $L_p$ | roll rate gain |
| $L_p / I_{xx}$ | roll rate damping = $2\zeta\omega_n$, 1/sec |
| $L_\phi$ | roll attitude gain, ft-lb/rad |
| p | body axis roll rate, rad/sec |
| $\dot{p}$ | body axis roll acceleration, rad/sec$^2$ |
| PIO | pilot induced oscillation |
| PR | pilot rating |
| $\delta$ | lateral stick deflection, in. |
| $\delta_{max}$ | maximum lateral stick deflection, in. |
| $\zeta$ | damping ratio = actual damping/critical damping |
| $\phi$ | euler angle roll attitude, rad, deg |
| $\phi_{ss}$ | steady state roll attitude, rad |
| $\phi_{ss}/\delta$ | bank angle sensitivity, rad/in. |
| $\frac{L_\delta}{I_{xx}} \delta_{max}$ | control power, rad/sec$^2$ |
| VFR | visual flight rules |
| $\omega_n$ | undamped natural frequency = $\sqrt{L_\phi / I_{xx}}$, rad/sec |
| $L_{gust}/L_{\delta_{max}}$ | ratio of gust intensity to roll control power |

## EQUIPMENT

A complete description of the Six-Degree-of-Freedom Motion Simulator and an evaluation of its suitability for simulating the visual hovering task are presented in reference 4. Briefly, the cab of the simulator is free to travel within a cube that is approximately 18 feet on a side. The cab also has angular motion of $\pm 45$ degrees about the roll, pitch and yaw axes. The piloting tasks were limited to those which could be accomplished within the motion limits of the simulator. Therefore, the scaling between the computed motion and simulator motion was one-to-one. The simulator cab was open (see figure 1) and large hangar doors in front of the simulator were opened to provide the pilot with visual cues of the outside real world. According to pilots' comments, the overall motion characteristics of the simulator provided a good representation of actual VFR hovering flight, and good agreement between simulator and flight data has been obtained on previous studies, such as the one reported in reference 4.

The roll-pitch controller was a conventional center stick which was fitted with a military B-8 grip. A spring-cartridge force-feel device (bungee) with replaceable springs was attached to the stick to give the desired force characteristics. Force measurements were made at the center of the stick grip, and these characteristics are discussed in the following section.

## EXPERIMENTS

The mechanical and computer controlled characteristics of the control systems are described in the following section. The scope of the experiment is indicated in Table 1, which presents the key control systems parameters and range of force gradients which were evaluated. All test conditions in Table 1 were evaluated for the VFR hover condition, without ground effect or gust disturbances. In addition, attitude systems were re-examined in the presence of an artificial gust disturbance.

### Controller Characteristics

Lateral Controller. - The tests covered a range of lateral force gradients from 0 to 3.1 lb/in. as shown in Table 1. Figures 2 through 7 show the various force characteristics which were used. When springs of the force-feel device (bungee) were made-up to produce gradients of 1.4 and 2.6 lb/in., the resultant gradients increased somewhat with stick displacement (figures 4 and 6), and were consequently used only for the acceleration and rate system studies of Pilot A. For all other tests the bungee produced constant gradients.

Each force-gradient spring was preloaded to just overcome friction. This resulted in a total break-out force of about ±0.6 lb in all cases. When the bungee was removed for the zero force-gradient studies, the breakout and friction were approximately zero.

Controller dead-band was always less than ±1/16 in.

The lateral controller had a maximum travel of ±5 in. throughout the study.

Longitudinal Controller.- Since little longitudinal maneuvering was to be done, the intent was simply to maintain enough harmony between axes to avoid interferring with the lateral evaluation. To accomplish this, three longitudinal force gradients were available to provide a lateral/longitudinal force gradient ratio as near to 1.0/1.5 as possible (this ratio was judged by the pilots to give good harmony). Longitudinal force gradients which were available were 0, 1.6, and 2.8 lb/in.

## Control and Stabilization Concepts

Lateral Control and Stabilization. - Optimum force gradients were determined for three typical concepts for controlling and stabilizing roll attitude: an unstabilized concept, a rate stabilized concept, and two versions of a rate plus attitude stabilized concept. These concepts will be referred to as the acceleration system, the rate syste, and the attitude systems. The mechanization of each system is illustrated in figure 8, and the values of key parameters are given in Table 1. These values are optimums as determined from reference 2 with the exception of the second attitude system. The natural frequency of this system was set high ($\omega_n$ = 4.0 rod/sec) as an example of a very "stiff" attitude system. Maximum control power was 2.5 rad/sec$^2$ for all systems.

Brief descriptions of each system, taken from reference 2, and sample time-history responses to step inputs are given in figure 9.

The acceleration system has no stabilizing feedback signals (path A in figure 8). A given lateral stick deflection will produce a steady-state angular acceleration, as shown in the time response of figure 9(a). The pilot must provide stability and angular-rate damping while controlling attitude. The control system parameters pertinent to this system are control power $\left(\frac{L_\delta}{I_{xx}} \cdot \delta_{max}\right)$ and control sensitivity $\left(\frac{L_\delta}{I_{xx}}\right)$.

The rate system is obtained simply by providing the acceleration system with angular-rate feedback (path A and B in figure 8). For this case, a given lateral stick deflection will produce a steady state angular rate, as shown in figure 9 (b). To control attitude, the pilot must provide attitude stability, but he does not need to worry about excessive rate build-up. The parameters associated with the rate system are control power, control sensitivity, and angular rate damping, $L_p/I_{xx}$. Damping is simply the gain of the rate feedback signal.

The attitude systems incorporate an attitude feedback signal in addition to the rate feedback signal (path A, B, and C in figure 8). For these systems, the pilot commands steady-state attitude proportional to lateral stick deflection, as shown in figure 9(c), and all stabilizing requirements are automatically provided. The parameters that describe the attitude system are control power, control sensitivity, rate damping, and undamped natural frequency, $(\omega_n)$.

The relationship of the attitude system parameters can be seen in the following derivation for steady-state roll attitude from the simplified equation for roll acceleration :

$$\dot{p} = \frac{L_\delta \cdot \delta}{I_{xx}} + \frac{L_\phi \cdot \phi}{I_{xx}} + \frac{L_p \cdot p}{I_{xx}}$$

since $\dot{p} = p = 0$ for a steady-state bank, the expression can be simplified and rearranged to:

$$\phi_{ss} = \frac{\delta\left(L_\delta/I_{xx}\right)}{\left(L_\phi/I_{xx}\right)}$$

since $L_\phi/I_{xx} = \omega_n^2$

$$\phi_{ss} = \frac{\delta\left(L_\delta/I_{xx}\right)}{\omega_n^2}$$

From the above equation, it can be seen that the higher the frequency, the higher the control displacement must be to achieve a given bank angle when control sensitivity is held constant, as it was in this study. With the attitude system, aircraft angular displacement and, consequently, steady-state linear translational velocity, is a function of stick displacement.

It follows that the maximum achievable $\phi_{ss}$ is a function of control power by substituting $\delta_{max}$ for $\delta$:

$$\phi_{ss_{max}} = \frac{C.P.}{\omega_n^2}$$

Longitudinal Control and Stabilization. - Longitudinal parameters were selected to provide a good rate system which would not interfere with the lateral axis evaluation. Control power, sensitivity, and damping were 1.0 rad/sec$^2$, 0.25 rad/sec$^2$/in., and 2.0/sec respectively.

Turbulence Characteristics

A random gust disturbance was generated on the analog computer by summing four sine-waves. The four sine waves were related by the expression:

$$\omega_i = 0.628 \frac{\pi(i-1)}{i} \qquad i = 1, 2, 3, 4$$

which provides a theoretically random wave form with a reasonable range of frequency content ($\omega_{max} = 7.75\ \omega_{min}$). A sample of the individual sine waves and the composite signal are shown in figure 10 .

This turbulence signal was introduced into the computations as a roll acceleration on the vehicle. The amplitude was adjusted to give maximum ratio of gust intensity to roll control power $\left(L_{gust}/L_{\delta max}\right)$ of 0.4. Only the two attitude systems were tested in the presence of turbulence.

## EVALUATION PROCEDURES

Tasks. - The simulator tasks were designed to establish a common basis for evaluation and consisted of: (1) a precision hover, (2) a slow lateral translational start-stop maneuver, and (3) a rapid transitional start-stop maneuver, translating from one side of the simulator travel to the other and back again as rapidly as possible. Tasks which required large amplitude control inputs for sustained periods of time were not possible because of the limited maneuvering space of the simulator. The simulator evaluation tasks were believed to be generally more demanding than actual flight because the confined maneuvering space of the simulator made the pilot aware of errors which might not be noticed in flight.

Pilots. - Two pilots participated in this control force characteristics study. Pilot A is a NASA pilot with X-14, XV-5A, and helicopter flight experience. Pilot B is an Air Force pilot with helicopter experience. Both are engineering test pilots, and both have considerable experience with the Six-Degree-of-Freedom Motion Simulator on various VTOL controls systems studies.

Pilot Rating Method. - The pilot rating (PR) scale used for this study was obtained from Reference 5, and is presented in Table II.

The pilot rated each of the three evaluation tasks, and the poorest of the three was taken as the PR for the test condition. This technique made it possible to determine specifically why a pilot preferred a particular force gradient in comparison to others. When an overall PR was given, it was determined by the most difficult task which was performed.

In this study, the pilot used the PR method to compare the various force gradients directly with each other for a given control system. A high confidence is therefore placed on the change in PR with control force gradient. The various control systems were not compared directly with each other (as was done in the study of reference 1) and less confidence is placed on the absolute value of PR.

## RESULTS AND DISCUSSIONS

Following is a summary of significant pilots' comments and discussions of each force gradient which was evaluated under the appropriate control system subsection. The resultant optimum control force gradient range for each condition and control system evaluated is presented in Table III with the specified values from references 2 and 3.

Acceleration System. - The data of Figures 11(a) and 11(b) reveal considerable difference in pilot rating trends, with respect to control force gradient, between the two pilots. Primarily, the ratings of Pilot A did not degrade as rapidly at higher force gradients as those of Pilot B. This difference may have been attributable to the nonlinearities of the bungee springs for the flagged data points of Pilot A (figure 11(a)). The force gradients of 1.4 and 2.6 lb/in. as plotted are average values, and the first inch of controller deflection actually gave only 0.8 and 1.9 lb/in. gradients respectively. Unfortunately, it was not possible for Pilot A to repeat the evaluations of these higher force gradients when the constant force gradient systems were made available. Because of these problems, only the data of Pilot B was used to determine the higher boundary of the optimum range for the acceleration system.

The major objection to higher force gradients with the acceleration system was that high forces limited the rate of control displacement in the rapid maneuvering task. Pilot B stated that the high gradient of 3.1 lb/in. was no problem for the spot hover task (PR = 3 1/2 to 4), but completely unsatisfactory (PR = 6 1/2 to 7) for rapid maneuvering. The objections may have been even greater for lower control sensitivity which would have required larger control displacements. It is also likely that, for the hover task, the pilots would have down graded the high force gradients if a gust disturbance had been introduced.

With a force gradient of 0.6 lb/in., Pilot B reported a tendency to over-control during rapid maneuvers, but considered this the best of the force gradients tested. Pilot A noted that the pitch force gradient of 1.6 lb/in. was too high for good harmony between axes. (0.9 lb/in. gradient in pitch would have satisfied the "ideal" ratio of 1.0/1.5 between lateral and pitch).

Both pilots stated that with a zero force gradient the task was more difficult because the system lacked stick centering characteristics. It is interesting that a small amount of friction, approximately ±0.5lb., would have been preferred over the zero friction system which was actually used.

Both pilots noticed an increase in control displacement frequency (control activity) as the force gradient was decreased from the optimum to zero. This created a tendency toward oscillatory response ("incipient PIO", in the words of the pilots), which consisted of overshoots in commanded roll attitude and general unsteadiness. This causes one to speculate that a genuine PIO condition could exist with gust disturbances or non-optimum control sensitivity (Reference 2 indicates a low frequency "wallowy" PIO with low control sensitivity, and a higher frequency PIO with high-control sensitivity).

The breakout forces (of about $\pm 0.6$ lb) used during this study did not produce pilot commentary until the lighter control force gradients were encountered.

With a low force gradient of 0.61b/in., Pilot B stated that the breakout force was too light. This was at first surprising because it was assumed that a high breakout force combined with a low force gradient would lead to an over-control condition. Actually, however, when a very light force gradient is installed, the breakout force must be high enough to prevent unintentional control motion.

In general, (for an acceleration system), the control force characteristics should provide positive centering with a breakout force that prevents unwanted control motion, and should not unduly limit the rate of stick displacement. From the data presented in Figure 11(b), an optimum force gradient range of 0.5 to 1.31b/in. was established.

Rate System. - Force gradient evaluations obtained with a rate system are presented in figures 12 (a) and 12 (b). Data agreement between pilots was better than for the acceleration system, although Pilot A again had the same non-linear gradients at the higher values. The data for Pilot A indicates essentially the same trend as for Pilot B at the higher values. That is, as the gradient increased beyond 1.4 lb/in., the steady hover task remained about PR = 2 or 2 1/2, but there was increasing objection to high forces required for rapid maneuvering. There appeared to be a limiting force gradient of about 1.75 lb/in. beyond which the pilots were consistent in their objections to rapid maneuvering.

Pilot B with a 3.1 lb/in. force gradient stated that the system was completely unsatisfactory ("too stiff") for rapid maneuvering. The high force gradient would have produced even poorer ratings if any of the control system parameters had been set at values which would require increased controller activity, such as lower control sensitivity or increased rate damping. Conversely, when the rate damping was actually reduced from $L_p/I_{xx} = -3.5$/sec to -1.5/sec, the pilot noted a slight improvement.

With 1.2 lb/in. gradient, Pilot B thought he had an attitude system with good maneuvering characteristics. When rate damping was reduced from $\frac{L_p}{I_x} = -3.5$/sec to -2.0 sec, he could then distinguish that he had a rate system. Figure 12 indicated 1.2 lb/in. to be nearly the optimum gradient for both pilots.

The pilots objected to the zero force gradient for two reasons. First, it required continuous effort to center the stick and prevent unwanted control motion when hovering. Second, it was easy to over-control when performing rapid maneuvers. Over-controlling during rapid maneuvering was still a problem when the force gradient was increased from zero to 0.6 lb/in.. This increased gradient, however, did make the hover task easier to perform because of improved stick centering.

Breifly, the control force characteristics for a rate system should provide prositive stick centering, be high enough to prevent over-controlling, and not so high as to limit the rate of control displacement. From the data presented in figure 12, an optimum force gradient range for a rate system was determined to be about 0.5 to 1.5 lb/in..

Attitude systems. - Two attitude systems were studied. The first had a natural frequency ($\omega_n$) of 2.0 rad/sec. This frequency is reported in reference 2 as representing the best compromise between aircraft response and stable hover. For certain VTOL applications, a more stable system could be selected to protect against upsets by external or self-induced disturbances; therefore, a second attitude system with $\omega_n = 4.0$ rad/sec was included in the control force gradient evaluation. A summary of key parameters for the attitude systems is included in Table I.

These systems were evaluated by the pilots in order of increasing force gradients, and commentary will be made in the same sequence.

$\omega_n = 2.0$ rad/sec. - ($L_p/I_{xx} = -3.6$/sec, $\zeta = 0.9$) With a zero force gradient, Pilot A did not detect the presence of attitude stabilization within the limited maneuvering space available, and Pilot B said that the advantages of attitude stabilization had been lost. Figures 13(a) and 13 (b) show an average PR of about 5, which is not as good as the rate system with zero force gradient (figure 12) and not much better than the acceleration system (figure 11). (This last observation should be tempered by the knowledge that the attitude systems were not compared directly with the acceleration systems.) Reference 2 specifies that the force gradient must supply a force equal to or greater than the breakout force in the first inch of travel. That is, the force gradient need merely to be zero or greater after the first inch of travel.

With a force gradient of only 0.6 lb/in, the pilots assigned ratings of 2 1/2 and 3 1/2 indicating a great improvement, although Pilot B did not yet consider it a superior system. Both pilots indicated a desire for better centering and/or a higher force gradient. In addition, both pilots noted a lack of "response harmony" with the 0.6 lb/in.

gradient, in that the control displacement was too large and control force too light to be compatible with resultant aircraft attitudes. The pilots ascribed this characteristic only to the attitude systems.

Force gradients of 1.2 and 1.8 lb/in. were within the optimum range and yielded pilot ratings from 2 to 2 3/4. The pilots disagreed on the relative merits of the two gradients. Pilot A had no preference between the two (for hover as well as maneuvering flight), while Pilot B definitely preferred the higher gradient, stating that 1.2 lb/in. was "a little loose" for the hover task; he also preferred the higher gradient for maneuvering.

With a gradient of 3.1 lb/in. the pilots agreed that the optimum range had definitely been exceeded, but disagreed on the ratings. Pilot A rated hover at PR = 1.0 with a 2 to 2 1/2 for rapid maneuvering, (noting that more effort was required than for 1.8 lb/in.). Pilot B rated hover at PR = 2 1/2 but rated rapid maneuvering at PR = 4 because of excessive "stiffness". The relatively poor PR for hover reflects this pilot's objection to high forces required even for the small control activity which was required to damp his own interogating inputs, and to check residual translational velocities.

The pilots speculated that they would have downgraded the higr force gradient even more if simulator lateral travel had been greater. The simulator's limited travel range of 18 feet did not permit holding large controller forces for any appreciable length of time. In actual flight, the pilots would have been free to command larger lateral aircraft displacements and would have been required to hold heavy forces for a longer period of time. The obvious fix of trimming out the forces would not apply in this type of maneuvering, and the pilots stated that to retrim to wings-level would probably increase his work load to the same level as holding the higher control forces. These comments are even more applicable to the $\omega_n$ = 4.0 rad/sec system, which had a much lower bank angle sensitivity ($\phi_{ss}/_\delta$ ratio) than the $\omega_n$ = 2.0 rad/sec system.

Referring again to figure 13, the $\omega_n$ = 2.0 rad/sec system is seen to have an optimum force gradient range, in calm air, from 1.0 to 2.5 lb/in.

Force gradients less than the 1.0 lb/in. minimum degraded the system more rapidly than gradients on the high side of optimum. The 1.0 lb/in. minimum requirement was established because with this system the pilot needed a force slightly larger than that required for positive stick centering to give him a clue to the amount of control displacement he had commanded. The size of small control inputs were judged primarily by sensing force rather than control displacement.

Note that the lower values of optimum force gradient range for the $\omega_n$=2.0rad/sec control system would provide good mechanical characteristics in the event of failure from the attitude system to the rate or acceleration systems.

$\underline{\omega_n = 4.0 \text{ rad/sec}}$. - ($L_p/I_{xx} = -4.0$ sec, $\zeta = 0.5$). The $\omega_n = 4.0$ rad/sec system resulted in a bank angle sensitivity of: $\phi_{ss}/_\delta = 1.8$ deg/in. (compared to $\phi_{ss}/_\delta = 7.5$ deg/in. for the $\omega_n = 2.0$ rad/sec system) which was on the lower boundary of the optimum range (equivalent to $L_p/I_{xx} = 0.5$ rad/sec$^2$/in.) as reported in reference 2. It is suspected that a higher bank angle sensitivity would have been a better choice, since several pilot comments referred to sluggish response.

Figure 14 reveals that a zero force gradient resulted in a system without any obvious benefits from attitude stabilization, as was the case for $\omega_n = 2.0$ rad/sec. Again the pilots complained of over-controlling during hover and overshooting the desired attitude during maneuvering flight. Pilot B emphasized that rapid maneuvering was more difficult that it was for the $\omega_n$ - 2.0 rad/sec system with zero force gradient.

A force gradient of 0.6 lb/in. produced a dramatic improvement in pilot rating. Pilot A thought this to be an optimum value with go centering for hover, and good force characteristics for maneuvering. Pilot B, however, objected to the poor "response harmony" (see comments in the $\omega_n = 2.0$ rad/sec section). It is suspected that Pilot B's primary objection was related to low bank angle sensitivity, although the point was not resolved.

Considering the next two gradients together (1.2 and 1.8 lb/in.), Pilot A said that there was little to distinguish them, and that the lighter gradient was slightly to be preferred (PR $\cong$ 1/4 better) but still on the heavy side for rapid maneuvering. Pilot B, however, thought that the 1.. lb/in. gradient was preferable because of lighter forces required for maneuvering, while it still had adequate centering for the hovering task. Although his ratings indicated the 1.2 lb/in. gradient to be optimum for $\omega_n = 4.0$ rad/sec, he objected to poor "response harmony". At 3.1 lb/in. gradient, both pilots considered the control force characteristics to be excellent for spot hovering, but the high forces required for maneuvering made the system marginally satisfactory for Pilot A (PR = 3 1/2) and completely unsatisfactory for Pilot B (PR = 6 1/2). Had the evaluations been done in actual flight, it is believed that the ratings would have been worse for Pilot A, as discussed in the preceding $\omega_n = 2.0$ rad/sec section.

In summary, the optimum range of force gradients for the $\omega_n = 4.0$ rad/sec system lies between 0.5 to 1.5 lb/in.. Gradients less than 0.5 lb/in. would result in rapid pilot degradation and appear to be a minimum acceptable gradient. Gradients above 1.5 lb/in. also result in rapidly degrading pilot ratings.

As was the case for the $\omega_n = 2.0$ rad/sec system, a gradient of about 1.0 lb/in. would again provide good force characteristics in the event of failure of the stabilizing feedbacks.

Effects of disturbances.- The effects of external gust-type disturbances on the pilot ratings for the various force gradients were investigated for both the $\omega_n$ = 2.0 rad/sec and 4.0 rad/sec attitude systems. This was done using an artificial disturbance, described in the Experiments section, which created random angular accelerations about the roll axis. A time history sample of the disturbance is shown in figure 10.

It was practicable to include only one level of peak disturbance intensity and, a peak value of 40% of maximum roll control power was selected. Figure 15, reproduced from reference 1, indicated this to be a value which gives appropriate PR degradation to both attitude systems being tested.

Pilot A performed all the evaluations for these tests, and the data are presented in figure 16. The results from his calm air evaluations are included for comparison.

For the $\omega_n$ = 2.0 rad/sec system in turbulence, the optimum range of gradients was 0.5 to 1.3 lb/in., which was well below the calm air optimum range. This was a result of increased controller activity to counteract the roll upsets. The higher force gradients degraded pilot ratings more quickly in disturbed air than in calm.

The optimum range of force gradients for the $\omega_n$ = 4.0 rad/sec system was unchanged from the calm air values of 0.5 to 1.5 lb/in.. There was apparently no objectionable increase in control usage to counteract roll upsets above that which was required for rapid maneuvering.

For the $\omega_n$ = 2.0 rad/sec system, the effect of turbulence was to decrease the calm air optimum range of force gradients in the direction of the 0.5 lb/in. value which the pilots considered to have poor response harmony. This characteristic was not as objectionable as the increased work load at values above 1.0 lb/in. gradient. Recurring observations of this nature emphasize the importance of optimizing all control parameters (i.e., mechanical characteristics, stabilizing feedbacks, control sensitivity, etc.) for the vehicle characteristics (i.e., turbulence response, ground effects, trim requirements, etc.) and the mission (i.e. task) requirements.

## SUMMARY AND CONCLUSIONS

A study of the effect of control force gradient on the VTOL visual hovering task was conducted on the NASA-Ames Research Center Six-Degree-of-Freedom Motion Simulator. Lateral control force-gradient characteristics were evaluated in combination with three different types of stabilization systems: an unstabilized (acceleration)system, a rate-stabilized system, and two attitude-stabilized systems. Force evaluations for the attitude systems were done with and without external gust disturbances. The results are summarized in Table III. The following conclusions were drawn from the results and discussions section:

1. A lateral control force gradient of 1.0 lb/in. was within the optimum range for all control systems and conditions which were evaluated. This value would be satisfactory for hovering and low speed maneuvering tasks when accompanied by low control dead band and a breakout force of approximately 0.6 lb. It would also appear to provide the best mechanical characteristics in the event of failure of stabilizing feedback signals (i.e., failure of an attitude or rate system to an acceleration system).

2. In certain instances, small variations from the optimum force gradient resulted in drastic degradation of a potentially superior system. For example, an attitude system of $\omega_n$ = 2.0 rad/sec in the presence of gust upsets would be degraded about two pilot ratings by a gradient change from 1.0 lb/in. to 2.0 lb/in..

3. Relatively small variations from the optimum force gradient range for a given control system had as great an effect on pilot rating as completely changing the type of control system stabilizing feedbacks. Examples of this phenomenon were the attitude stabilized control systems. When the force gradient was reduced to near zero, these systems were little better than an acceleration control system.

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| LATERAL CONTROL SYSTEM | EVALUATION PILOT | FORCE GRADIENT lb/in. | MAX. CONTROL DISPLACEMENT. in. | CONTROL SENSITIVITY, rad/sec²/in. | CONTROL POWER, rad/sec² | ROLL RATE DAMPING 1/sec | NATURAL FREQUENCY rad/sec | DAMPING RATIO | RATIO OF GUST INTENSITY TO CONTROL POWER |
|---|---|---|---|---|---|---|---|---|---|
| ACCELERATION | A B | 0 | ±5.0 | 0.5 | ±2.5 | | | | |
| | A B | 0.6 | | | | | | | |
| | A B | 1.2 | | | | | | | |
| | A | 1.4 | | | | | | | |
| | B | 1.8 | | | | | | | |
| | A | 2.6 | | | | | | | |
| | B | 3.1 | | | | | | | |
| RATE | A B | 0 | ±5.0 | 0.5 | ±2.5 | -3.5 | | | |
| | A B | 0.6 | | | | | | | |
| | A B | 1.2 | | | | | | | |
| | A | 1.4 | | | | | | | |
| | B | 1.8 | | | | | | | |
| | A | 2.6 | | | | | | | |
| | B | 3.1 | | | | | | | |
| ATTITUDE, $\omega_n = 2.0$ rad/sec | A B | 0 | ±5.0 | 0.5 | ±2.5 | -3.6 | 2.0 | 0.9 | 0.4 (PILOT A ONLY) |
| | A B | 0.6 | | | | | | | |
| | A B | 1.2 | | | | | | | |
| | A B | 1.8 | | | | | | | |
| | A B | 3.1 | | | | | | | |
| ATTITUDE, $\omega_n = 4.0$ rad/sec | A B | 0 | ±5.0 | 0.5 | ±2.5 | -4.0 | 4.0 | 0.5 | 0.4 (PILOT A ONLY) |
| | A B | 0.6 | | | | | | | |
| | A B | 1.2 | | | | | | | |
| | A B | 1.8 | | | | | | | |
| | A B | 3.1 | | | | | | | |

TABLE I.- SCOPE OF EXPERIMENT

PROPOSED PILOT OPINION RATING SYSTEM FOR UNIVERSAL [illegible]

| | ADJECTIVE RATING | NUMERICAL RATING | DESCRIPTION | PRIMARY MISSION ACCOMPLISHED? | CAN BE LANDED |
|---|---|---|---|---|---|
| NORMAL OPERATION | Satisfactory | 1 | Excellent, includes optimum | Yes | Yes |
| | | 2 | Good, pleasant to fly | Yes | Yes |
| | | 3 | Satisfactory, but with some mildly unpleasant characteristics | Yes | Yes |
| EMERGENCY OPERATION | Unsatisfactory | 4 | Acceptable, but with unpleasant characteristics | Yes | Yes |
| | | 5 | Unacceptable for normal operation | Doubtful | Yes |
| | | 6 | Acceptable for emergency condition only* | Doubtful | Yes |
| NO OPERATION | Unacceptable | 7 | Unacceptable even for emergency condition * | No | Doubtful |
| | | 8 | Unacceptable - dangerous | No | No |
| | | 9 | Unacceptable - uncontrollable | No | No |
| | Unprintable | 10 | x!@ [illegible]!! Did not get back to report | What mission? | |

*(Failure of a stability augmenter)

TABLE II.- NASA PILOT OPINION RATING SCALE

| LATERAL CONTROL SYSTEM | OPTIMUM FORCE GRADIENT RANGE, lb/in |
|---|---|
| ACCELERATION | 0.5 to 1.3 |
| RATE | 1.0 to 1.5 |
| ATTITUDE, $\omega_n = 2.0$ rad/sec | 0.5 to 2.5 |
| ATTITUDE $\omega_n = 4.0$ rad/sec | 0.5 to 1.5 |
| ATTITUDE $\omega_n = 2.0$ rad/sec WITH TURBULENCE | 0.5 to 1.3 |
| ATTITUDE $\omega_n = 4.0$ rad/sec WITH TURBULENCE | 0.5 to 1.5 |
| REFERENCE 2[1] | 0.5 to 2.0 |
| REFERENCE 3[1] | 0.5 to 2.0 |

1. A RATE CONTROL SYSTEM IS IMPLIED.

TABLE III. - SUMMARY OF VTOL LATERAL CONTROL FORCE GRADIENT EVALUATION

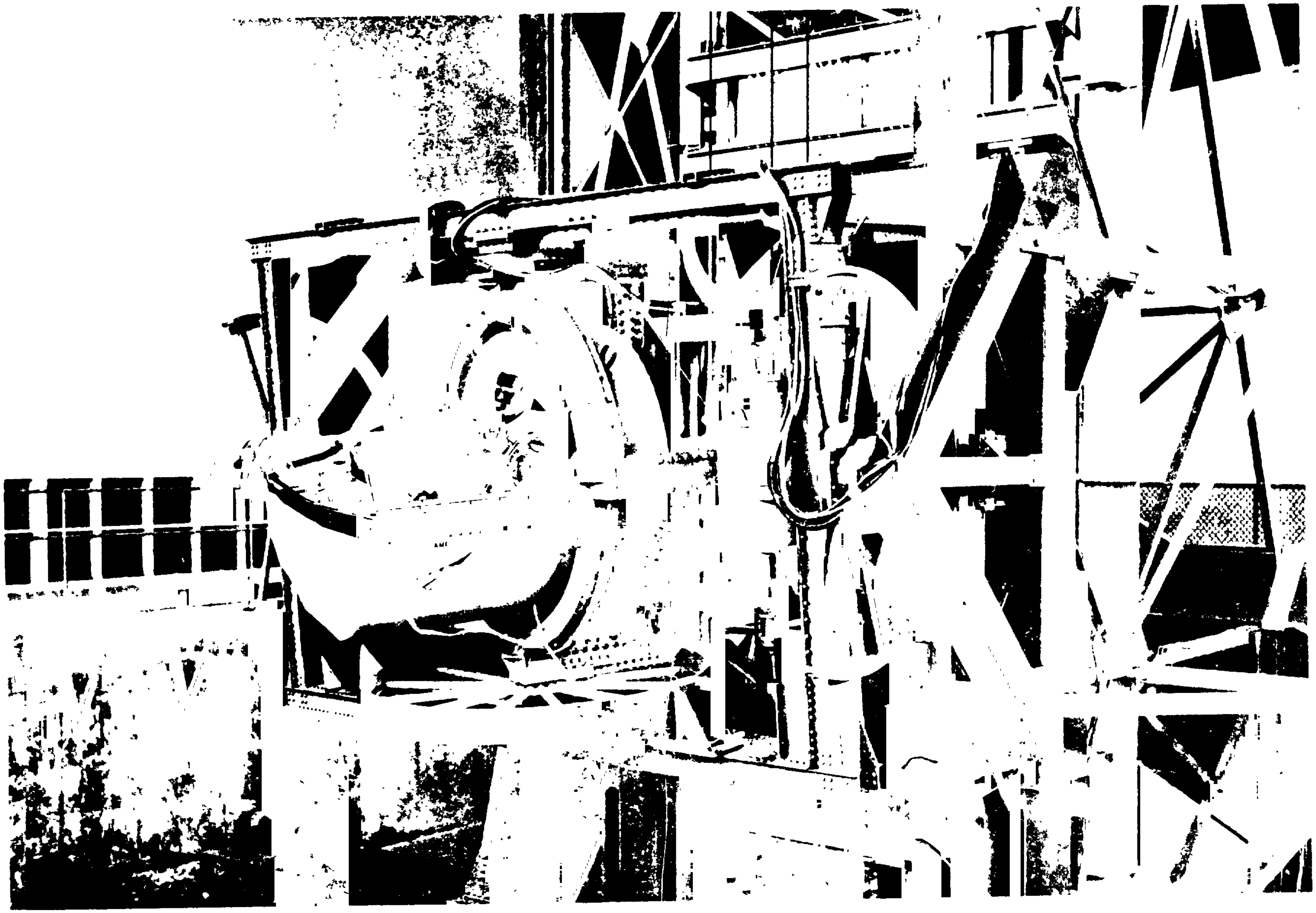


FIGURE 1.- SIX-DEGREE-OF-FREEDOM SIMULATOR

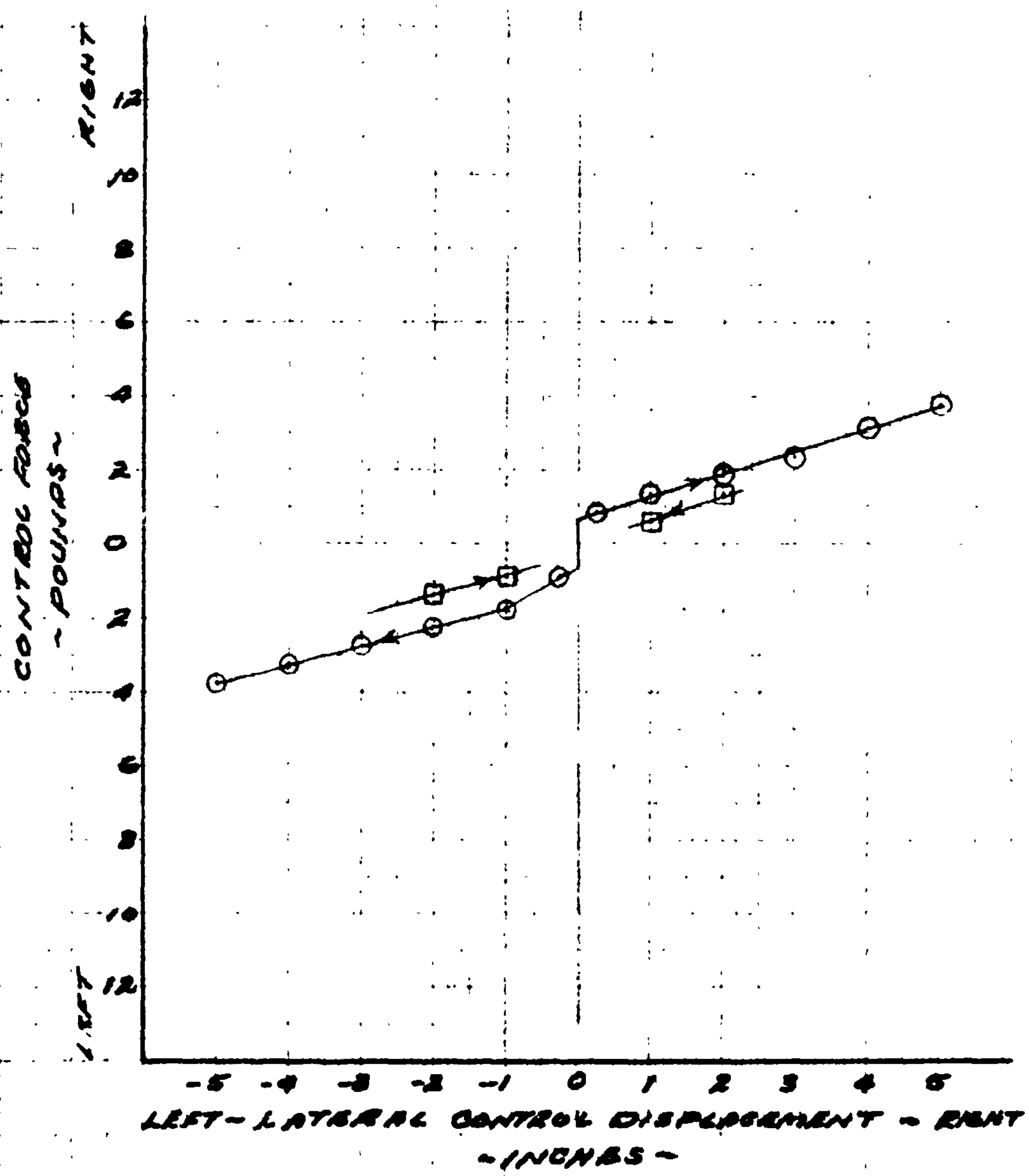



FIGURE 2.- LATERAL CONTROLLER FORCE CHARACTERISTICS
AVERAGE GRADIENT = 0.6 lb/in.

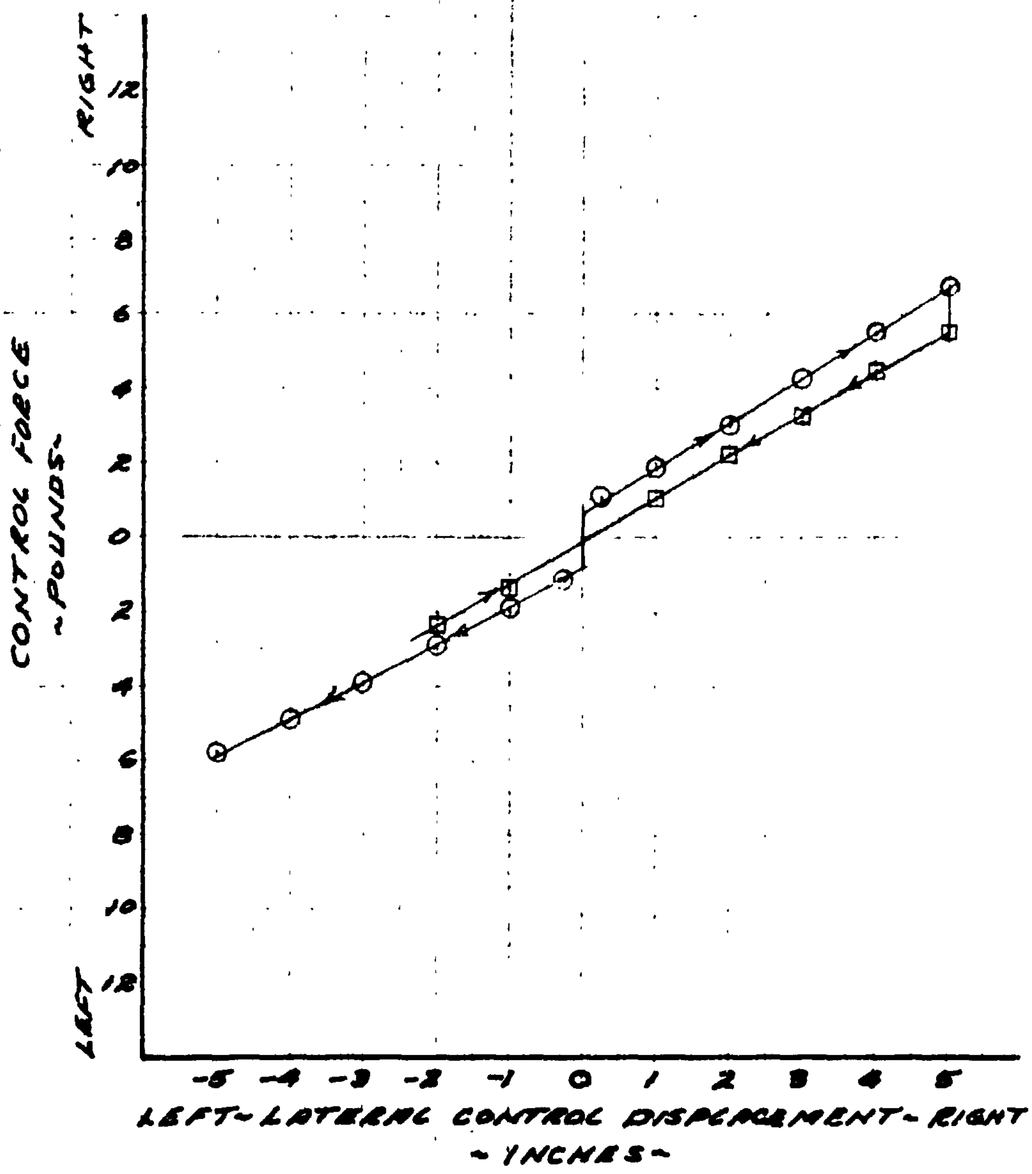



FIGURE 3.- LATERAL CONTROL FORCE CHARACTERISTICS
AVERAGE GRADIENT = 1.2 lb/in.

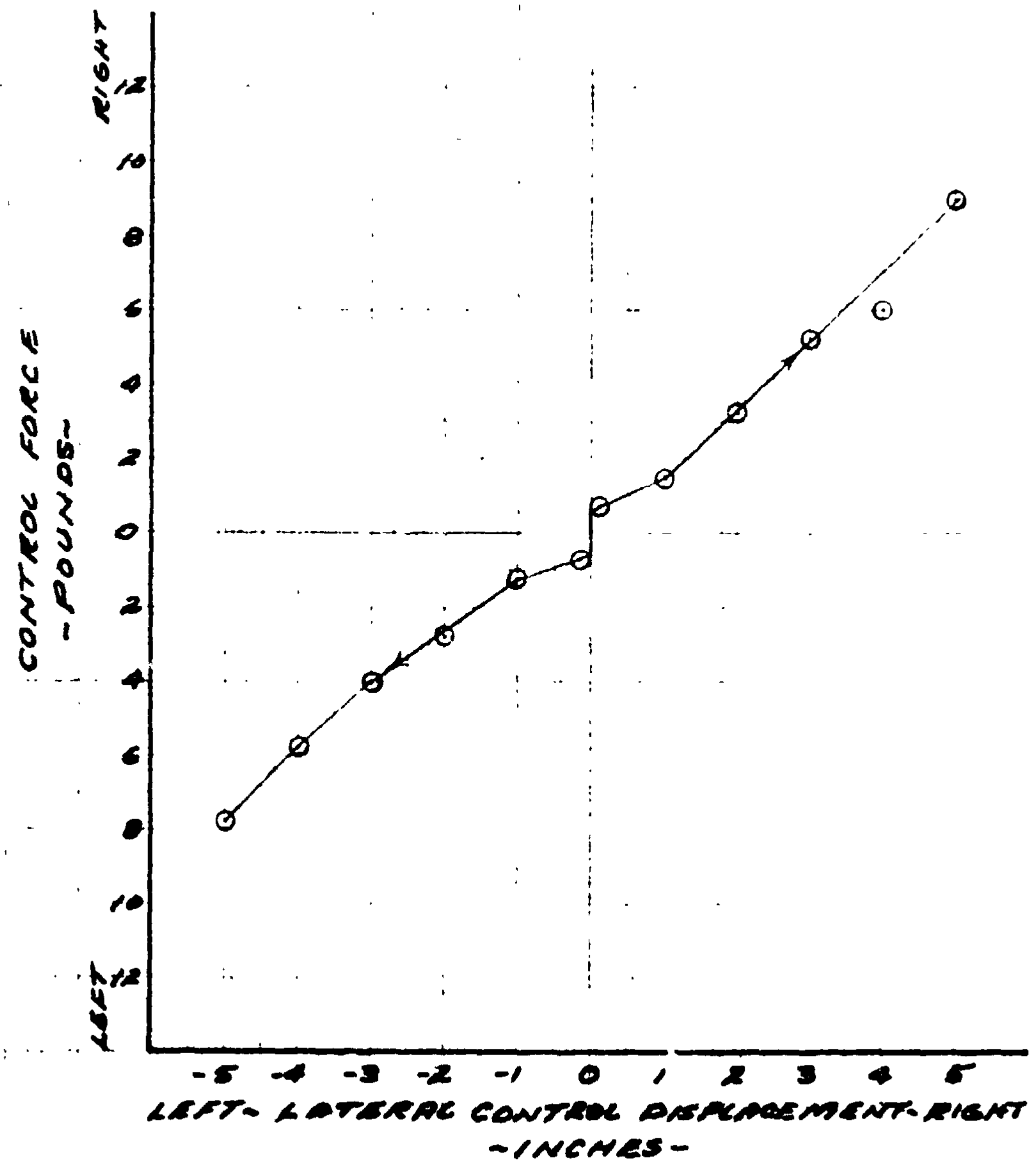



FIGURE 4.- LATERAL CONTROLLER CHARACTERISTICS
AVERAGE FORCE GRADIENT = 1.4 lb/in.

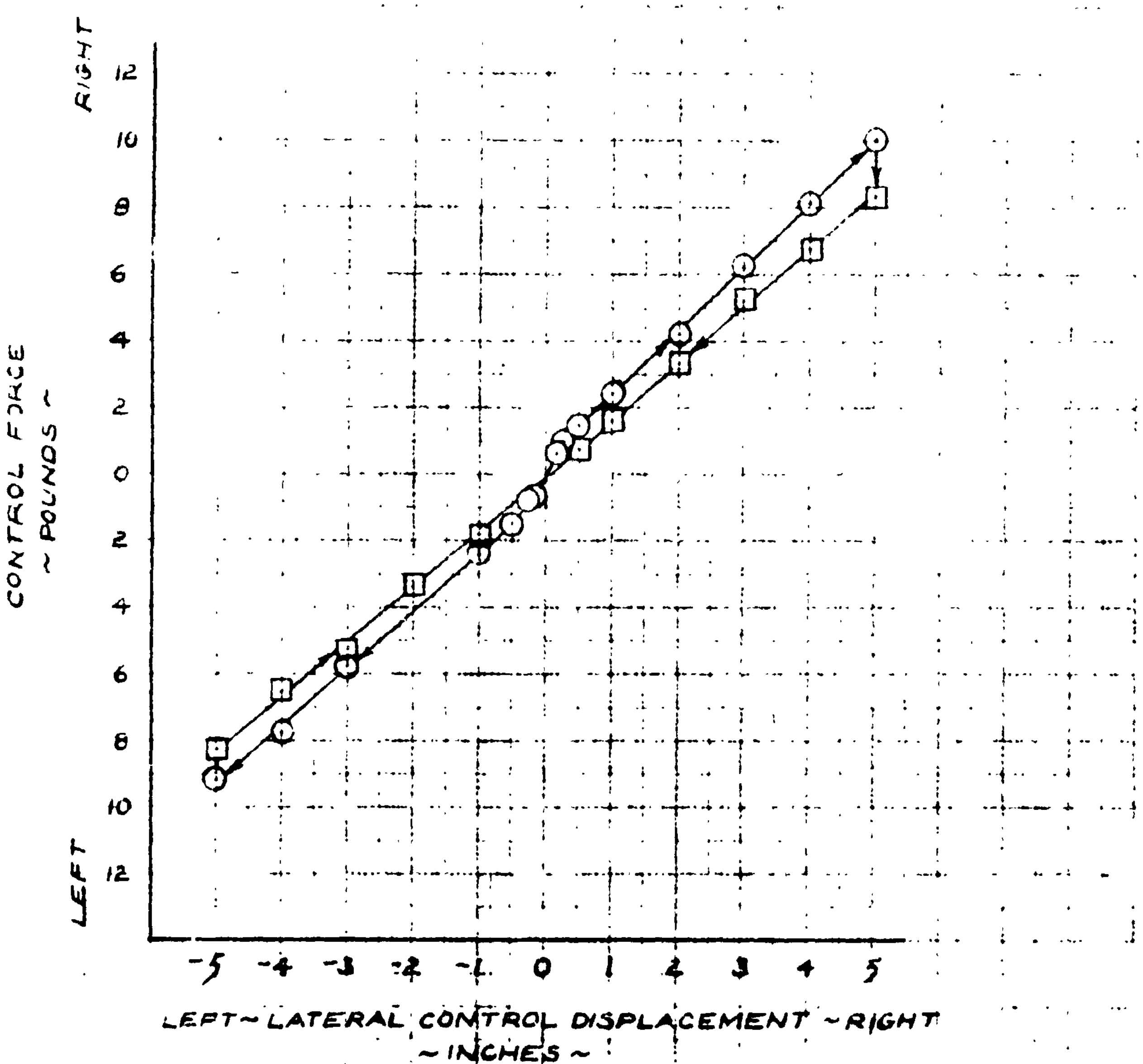



FIGURE 5.- LATERAL CONTROLLER FORCE CHARACTERISTICS. FORCE GRADIENT = 1.8 lb/in.

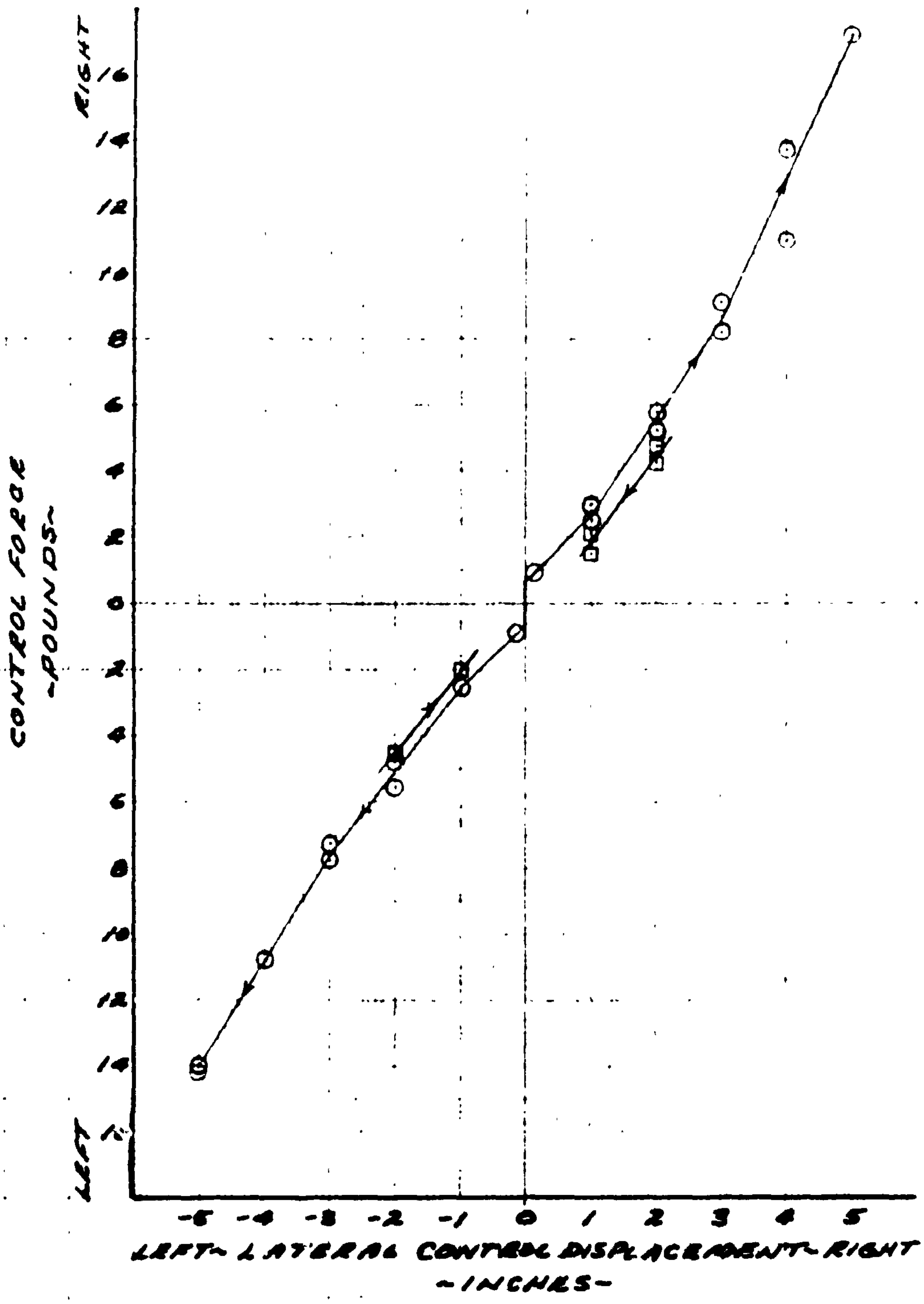



FIGURE 6.- LATERAL CONTROLLER FORCE CHARACTERISTICS
AVERAGE GRADIENT = 2.6 lb/in.

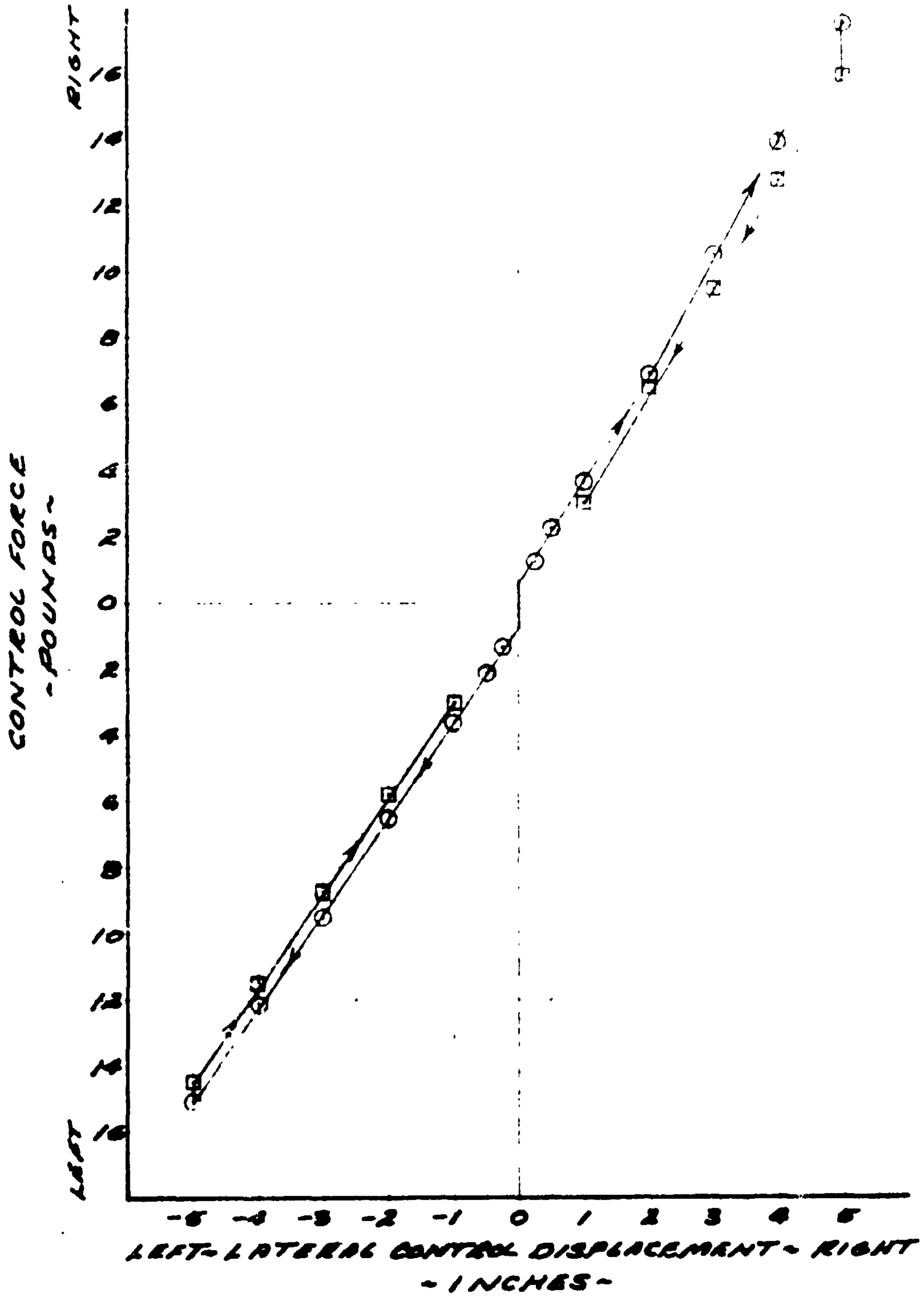
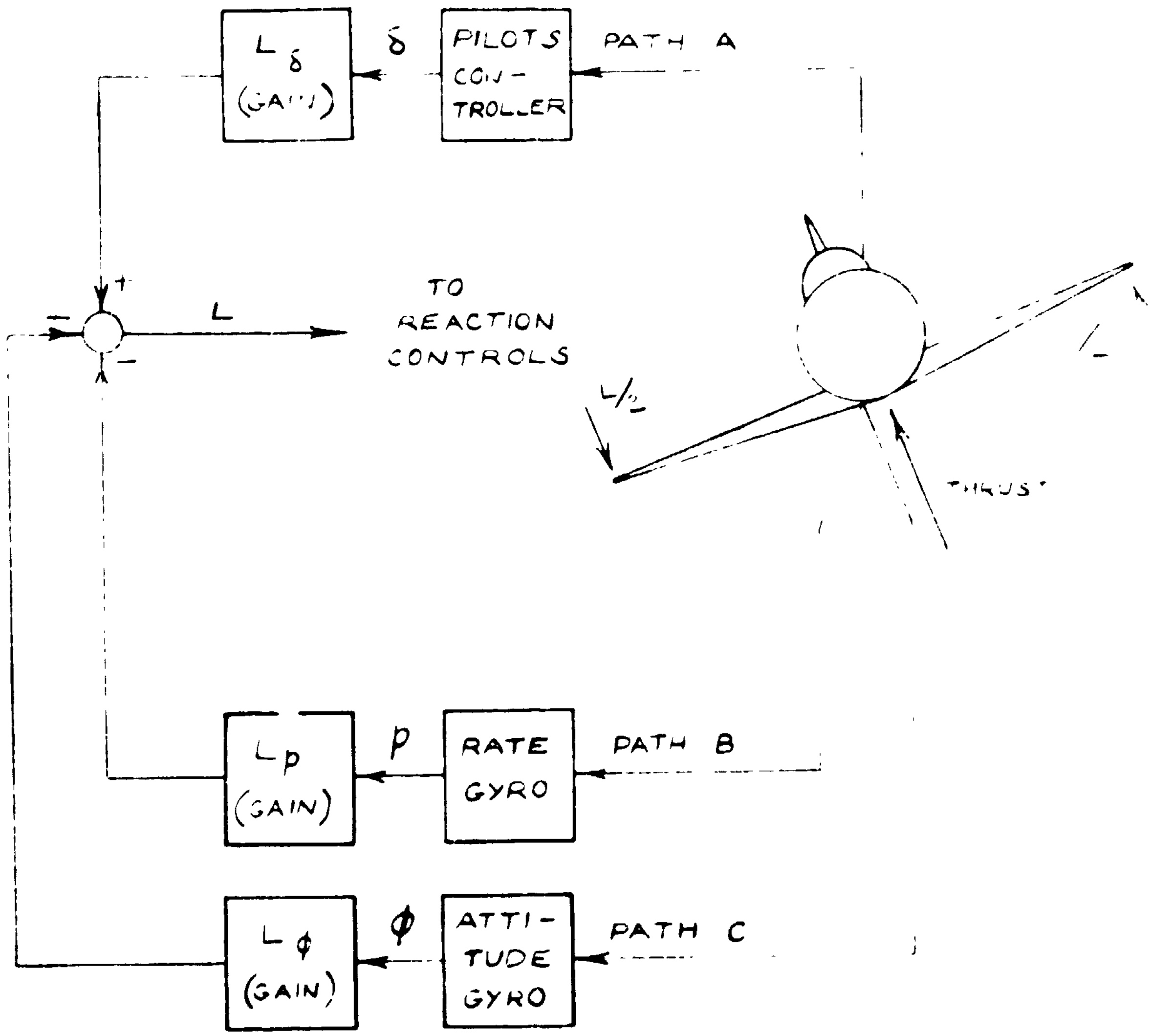



FIGURE 7.- LATERAL CONTROLLER FORCE CHARACTERISTICS
AVERAGE GRADIENT = 3.1 lb/in.




PATH A ONLY: ACCELERATION CONTROL SYSTEM

PATH A + B: RATE CONTROL SYSTEM

PATH A + B + C: ATTITUDE CONTROL SYSTEM

FIGURE 8.- SCHEMATIC OF ACCELERATION, RATE, AND ATTITUDE VTOL CONTROL SYSTEMS

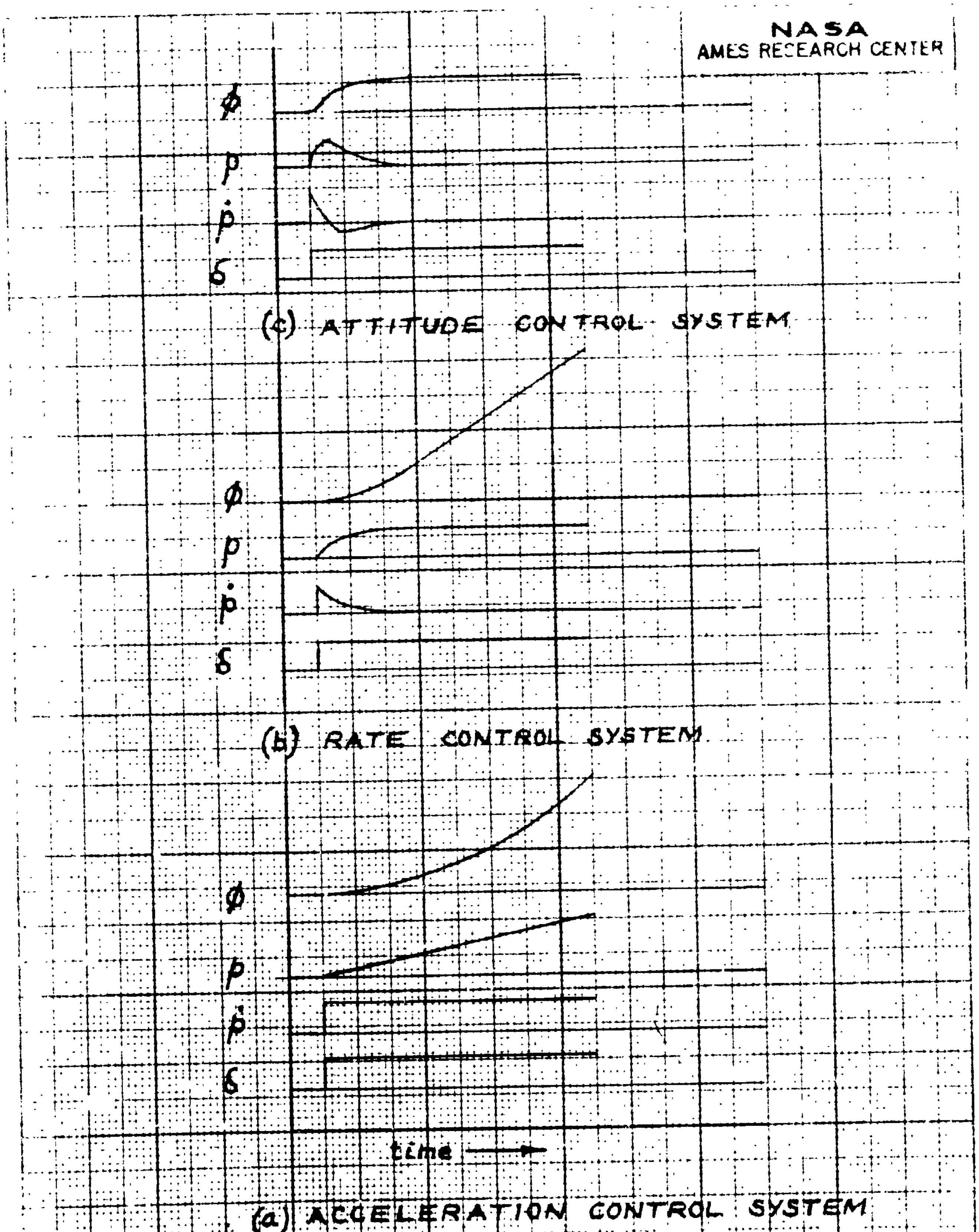



FIGURE 9.- EXAMPLE TIME HISTORY RESPONSES OF VTOL CONTROL SYSTEMS TO A STEP-CONTROL INPUT

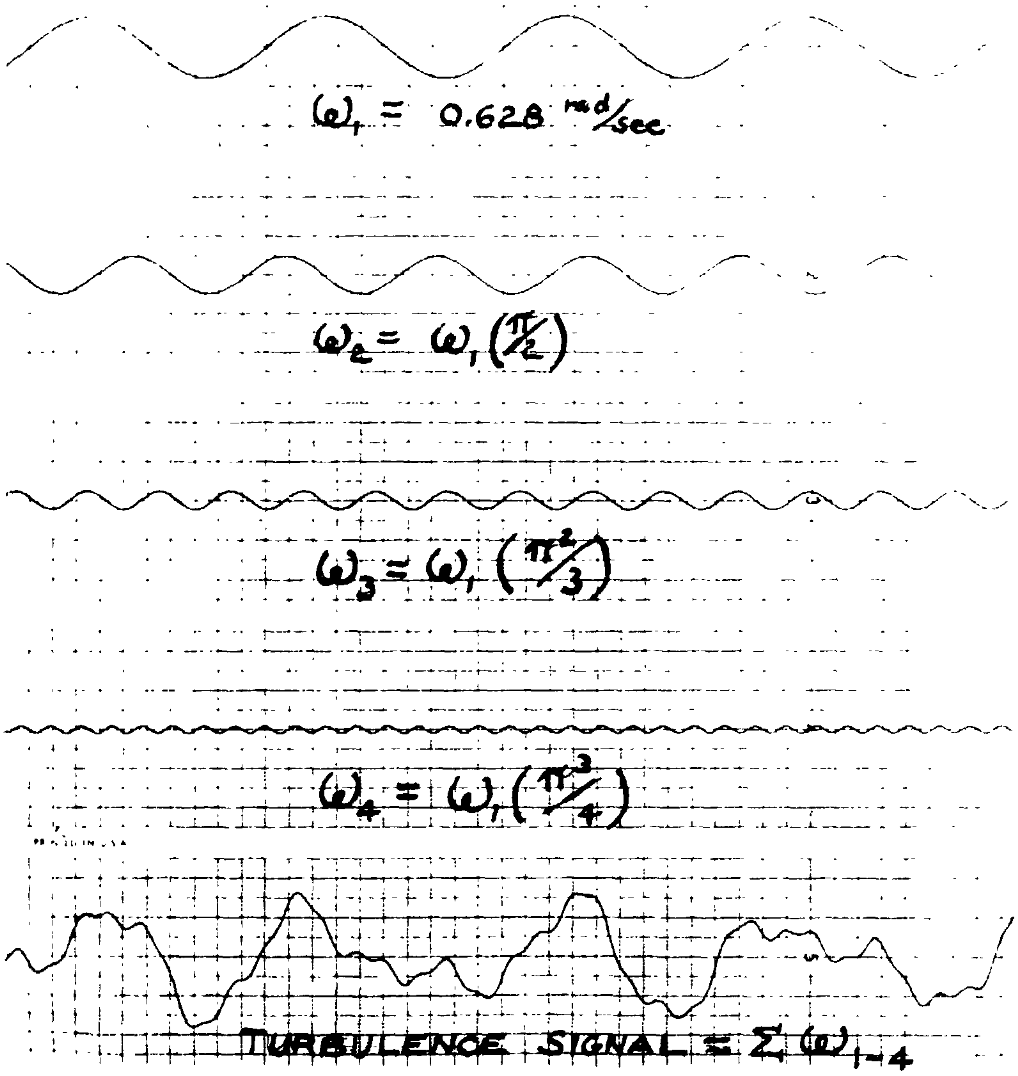



FIGURE 10.- GENERATION OF THE TURBULENCE SIGNAL

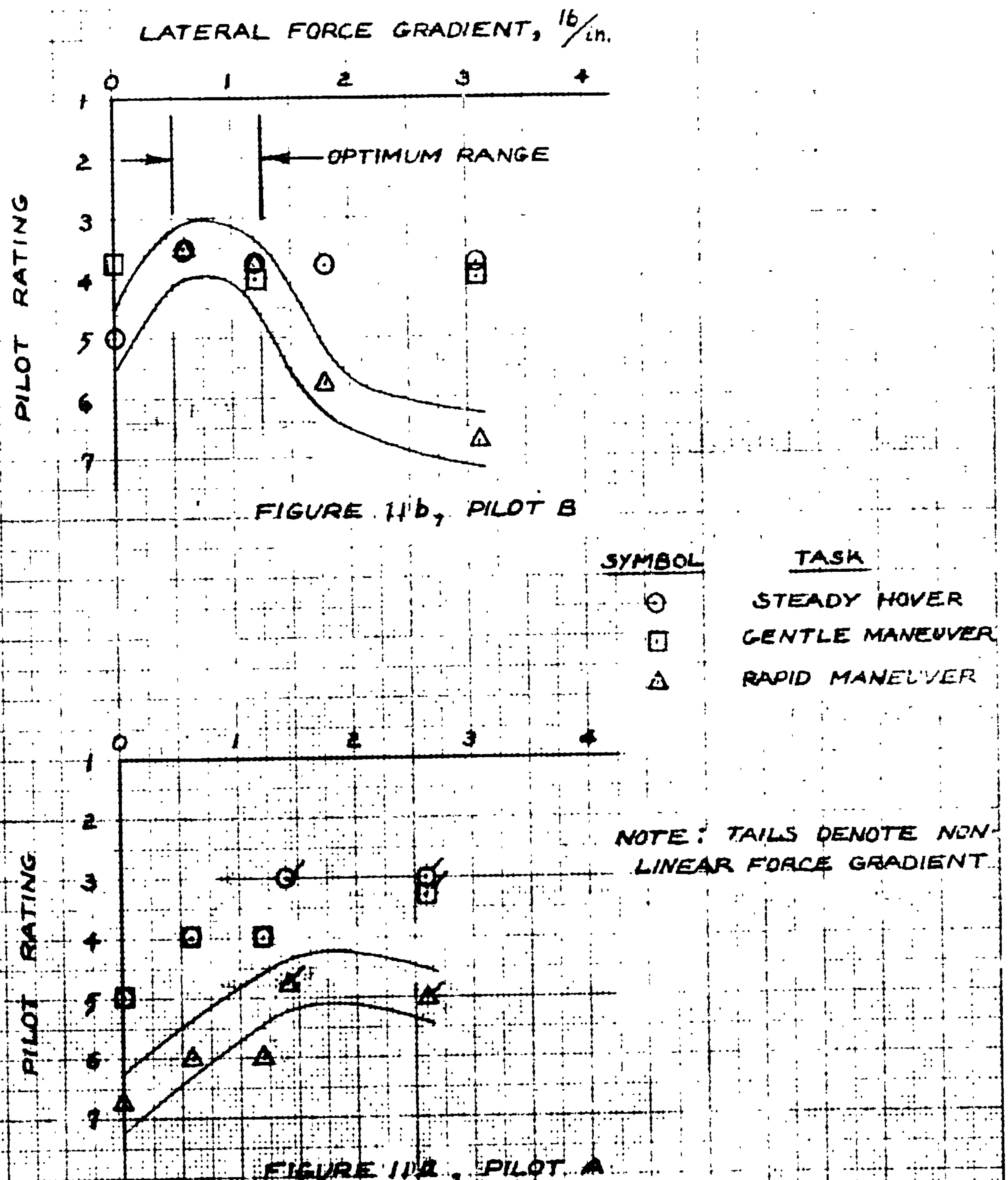



FIGURE 11.- EFFECT OF LATERAL FORCE GRADIENT ON THE VTOL HOVERING TASK USING AN ACCELERATION CONTROL SYSTEM

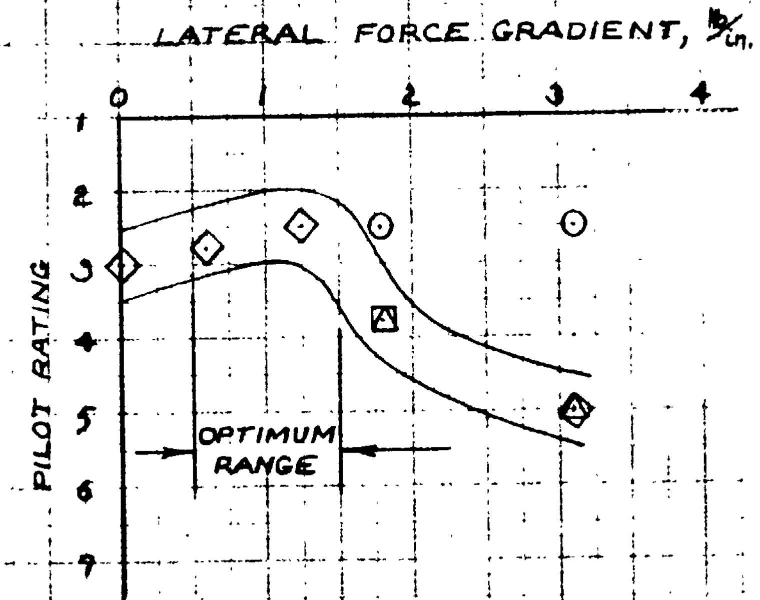



FIGURE 12 b, PILOT B

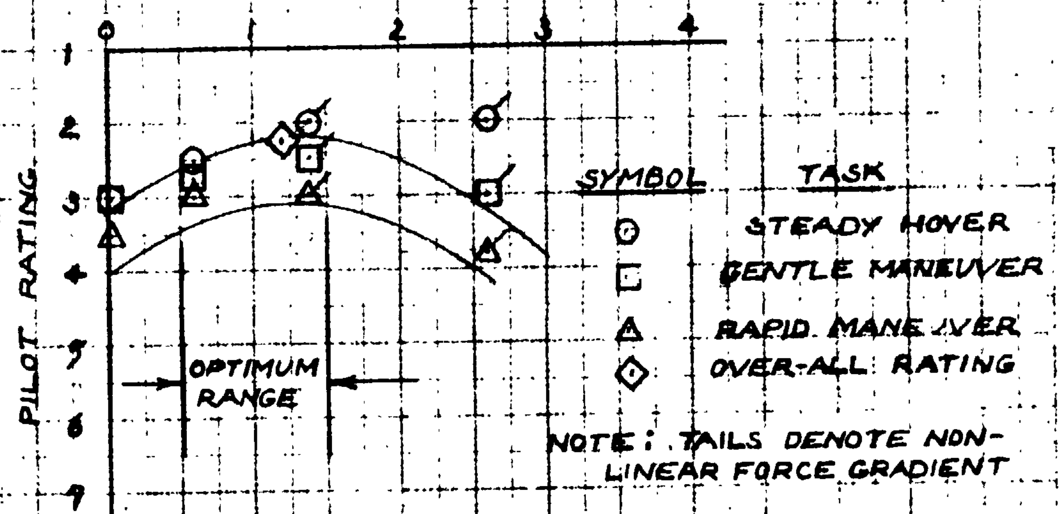



FIGURE 12 a, PILOT A

FIGURE 12. - EFFECT OF LATERAL FORCE GRADIENT ON THE VTOL HOVERING TASK USING A RATE CONTROL SYSTEM

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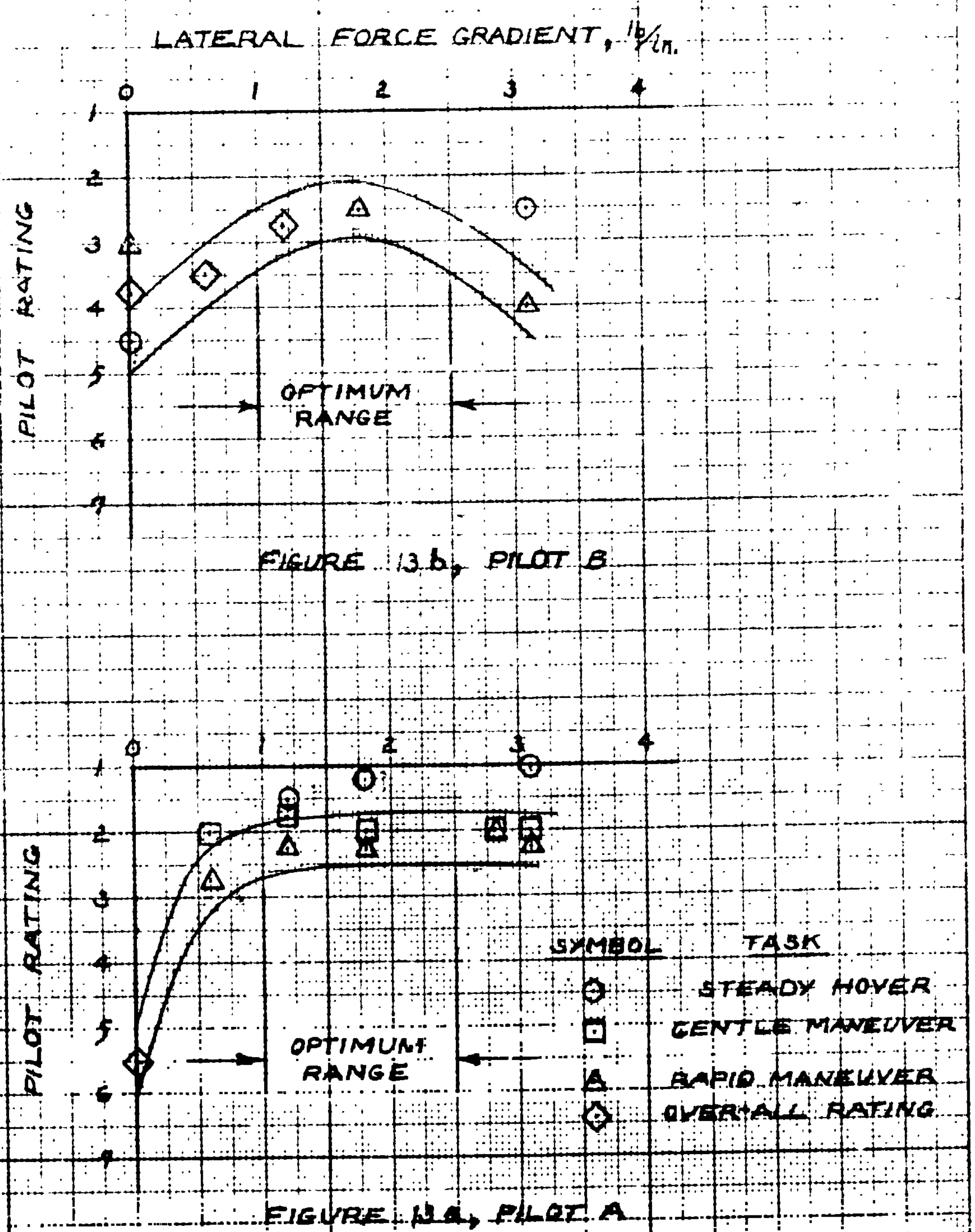


FIGURE 13.- EFFECT OF LATERAL FORCE GRADIENT ON THE VTOL HOVERING TASK USING AN ATTITUDE CONTROL SYSTEM, $\omega_n = 2.0$ rad/sec

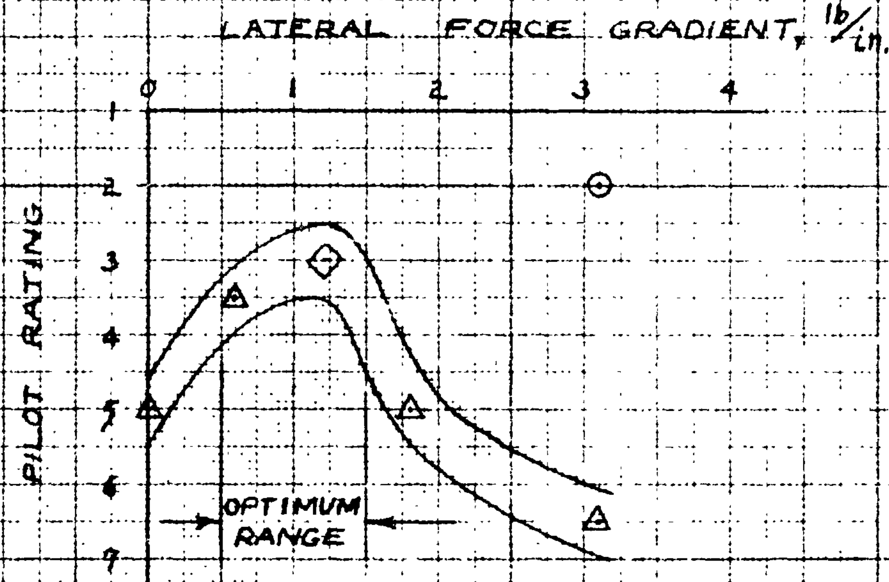


FIGURE 14b, PILOT D

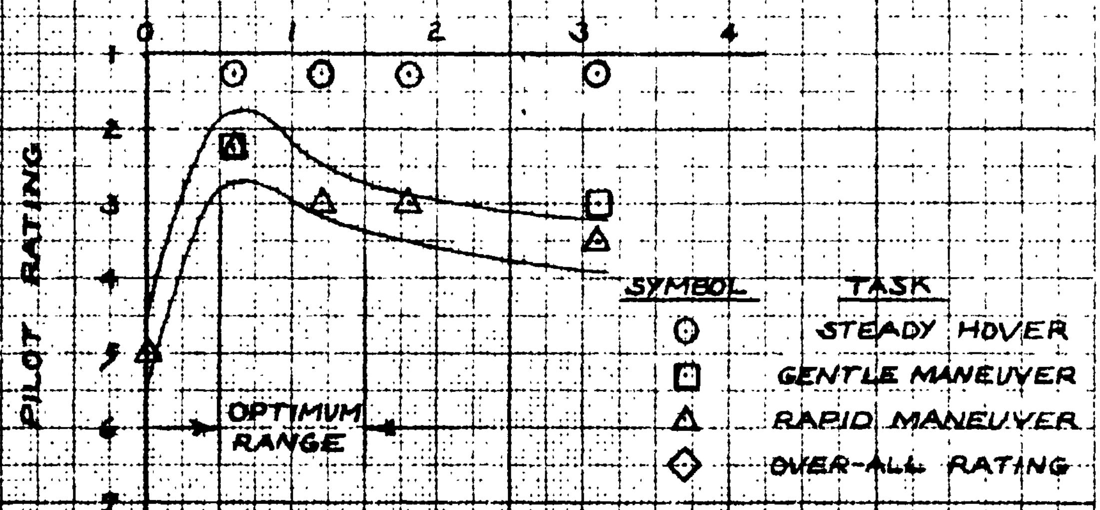


FIGURE 14a, PILOT A

FIGURE 14.— EFFECT OF LATERAL CONTROL GRADIENT ON THE VTOL HOVERING TASK USING AN ATTITUDE CONTROL SYSTEM, $\omega_n = 4.0$ rad/sec

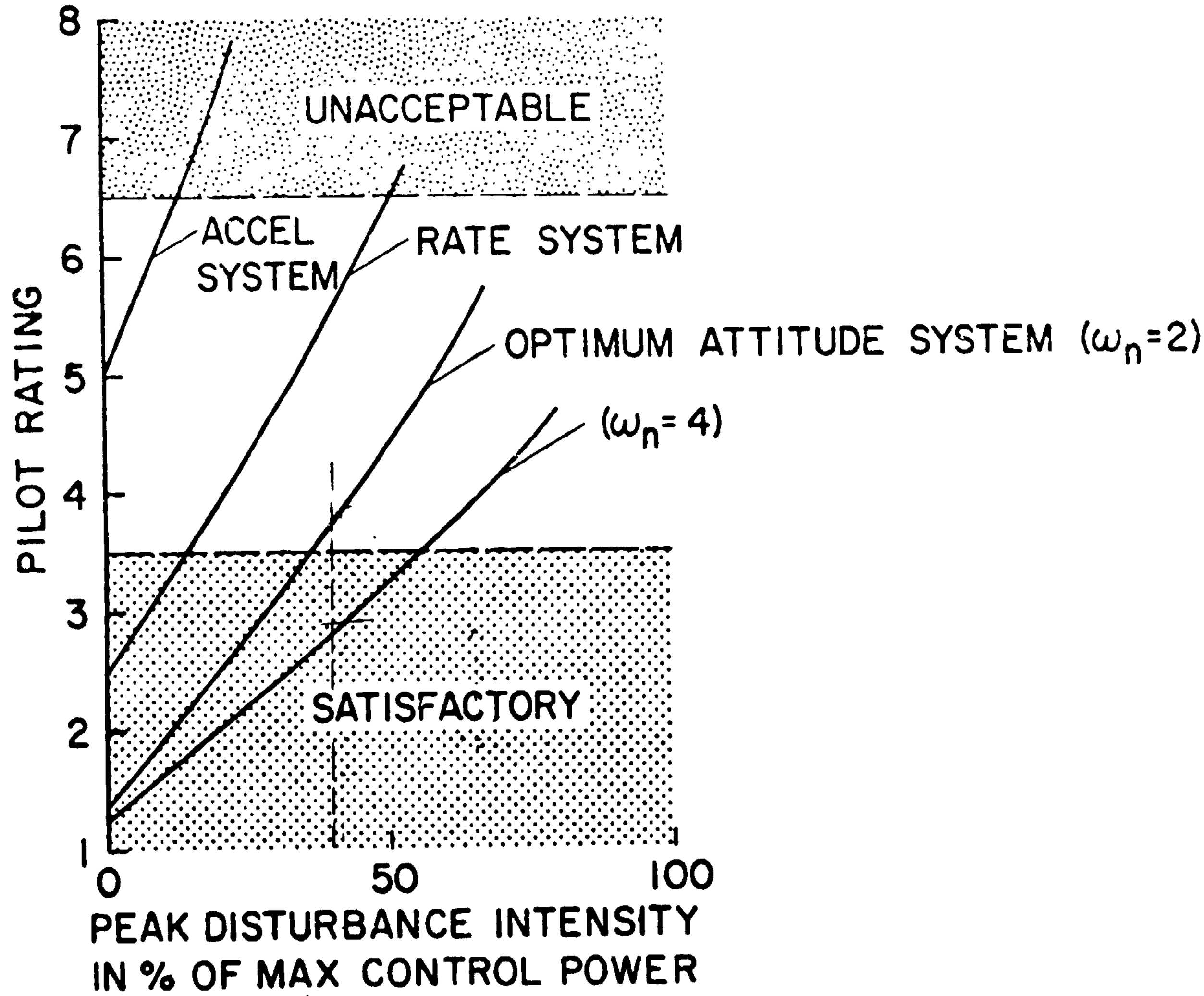


FIGURE 15. - EFFECT OF DISTURBANCE INTENSITY ON THE HOVER TASK (FROM REF. 1)

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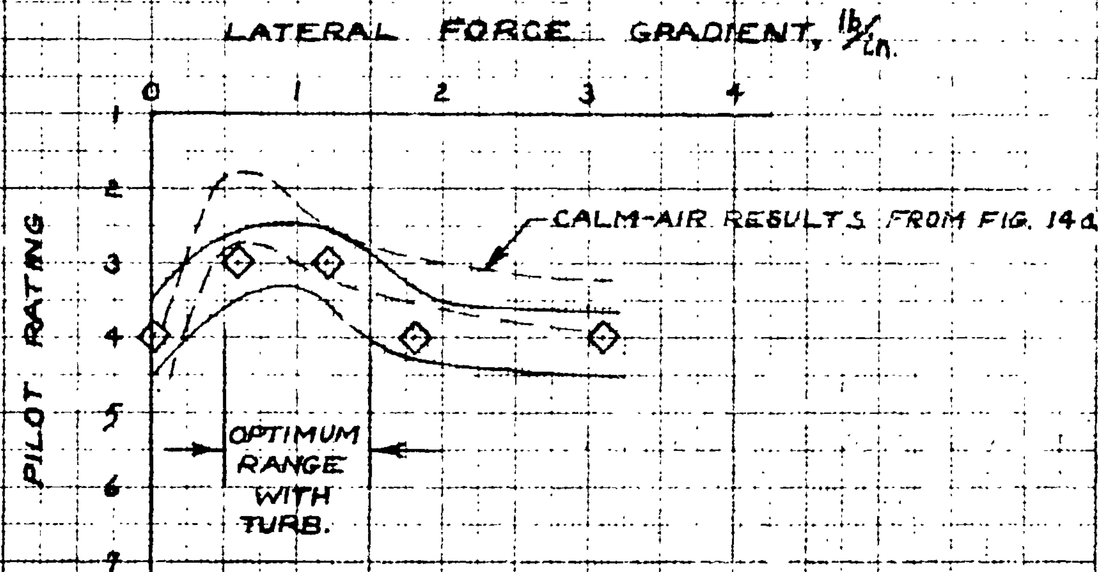


FIGURE 16 b, $\omega_n = 4.0$ rad/sec
PILOT A

NOTE: $L_{GUST}/L_{\delta_{MAX}} = 0.4$

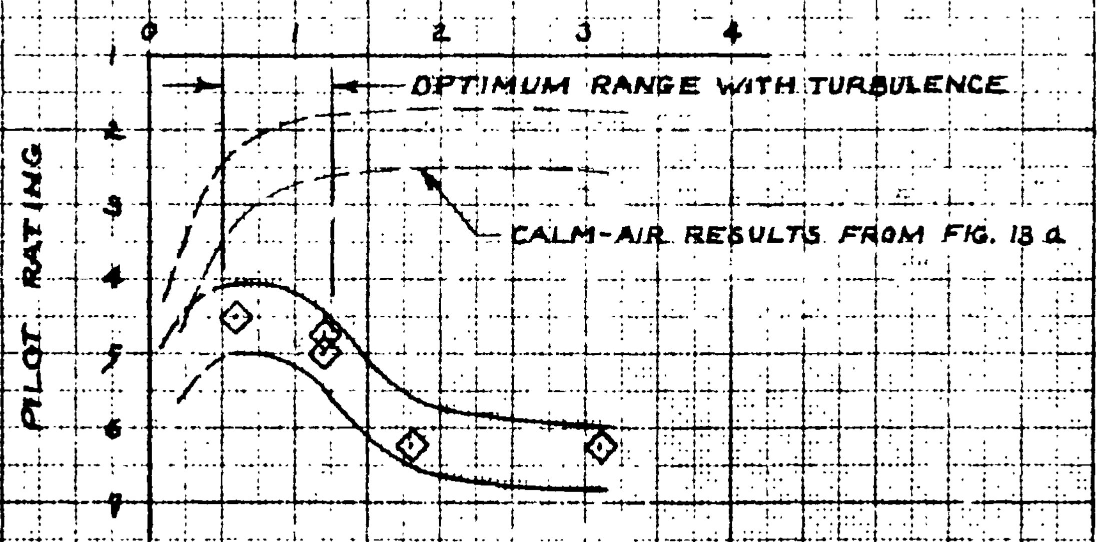


FIGURE 16 a, $\omega_n = 2.0$ rad/sec
PILOT A

FIGURE 16.- EFFECT OF LATERAL FORCE GRADIENT ON THE VTOL HOVERING TASK USING ATTITUDE CONTROL SYSTEMS IN THE PRESENCE OF TURBULENCE